A Systems Perspective on Advancing Earth System Prediction

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Outline

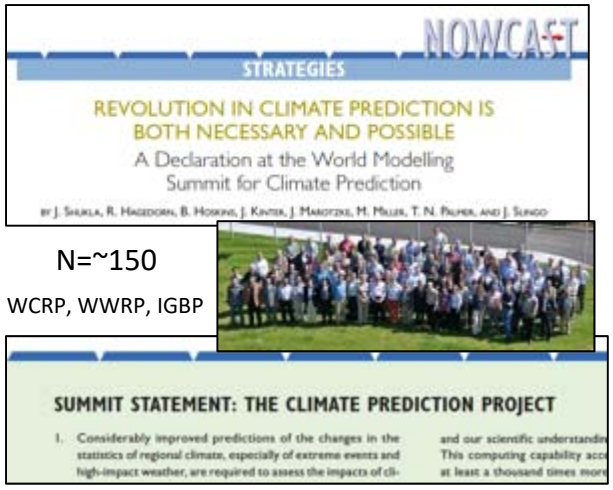
- Preamble
- Visions/ideas, funding/budgets, what else might help?
- Systems Engineering & Systems of Systems Approaches to Complex Problems
- Considerations for Advancing Earth System Prediction

Preamble

- A “predictable” ☺ S2S Scientist
- Exposure to Systems Approaches / Engineering
- BASC’s Weather Enterprise Study Considerations
  - **AGU 2019 Centennial Session:** A Systems Perspective on the Environmental Prediction Enterprise
- RFI Input

Ideas & Vision : Have we been here before?

May 6-9, 2008

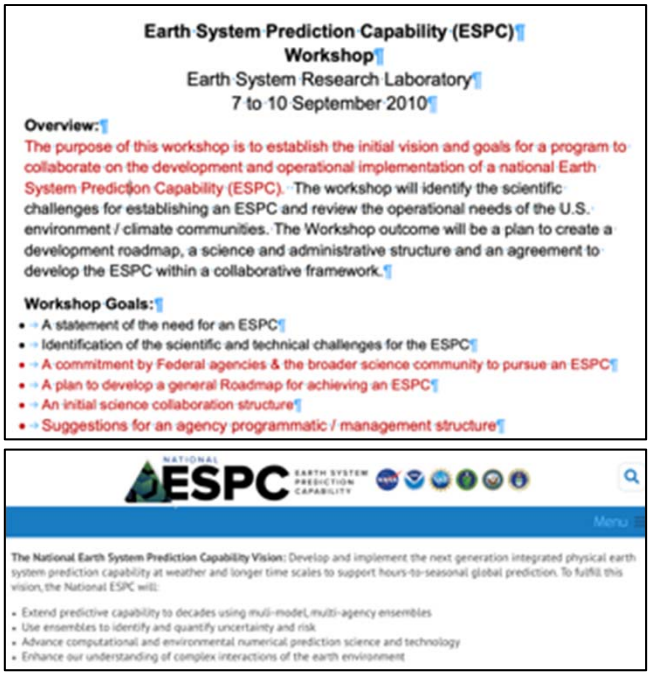


N=~150

WCRP, WWRP, IGBP

- *Focused Modeling Initiative*
- *Improve H/W + S/W*
- *Process Focused Model Evaluation*
- *Data Assimilation*
- *Ensembles*
- *Cooperation/Coordination*
- *etc*

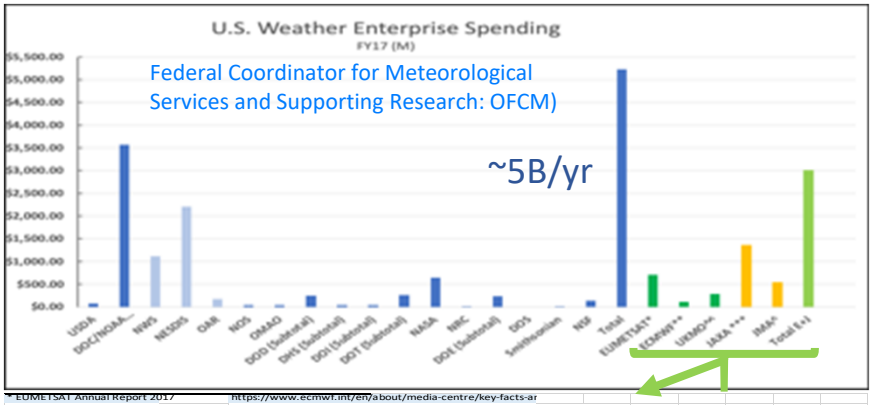
Sep 7-10, 2010



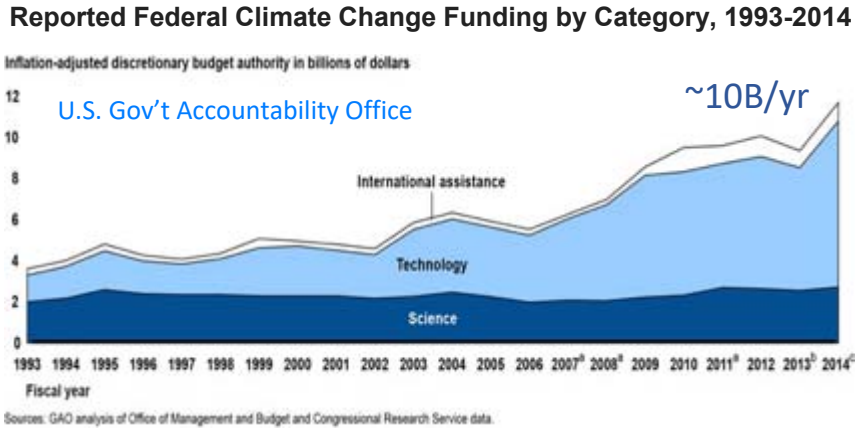
NASEM 2003-18

We have been awash in good ideas and intentions for a decade or more.

Funding & Budgets : Is the solution always more $?



* EUMETSAT Annual Report 2017 https://www.ecmwf.int/en/about/media-centre/key-facts-ar
** ECMWF Annual Repor 2017 https://www.ecmwf.int/sites/default/files/elibrary/2018/18309-annual-report-2017.pdf
***2017 https://global.jaxa.jp/about/president/presslec/201701.html
^ 2012 https://en.wikipedia.org/wiki/Japan_Meteorological_Agency
^^ 2017 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633793/met-office-annual-report-2016-17-web.pdf



The E. Rutherford Challenge

"[Ladies and] Gentlemen, we have run out of money. It's time to start thinking."

- Can we get more out of what we have or more from the additional funding we may be entrusted with?
- Once the $ is fixed, and the general ideas are in place, what are the modern practices to derive the most benefit from the $?
- The challenge/opportunity we face is bigger than any one entity/agency – how do we put the puzzle pieces together in a way that leverages the strength of each?

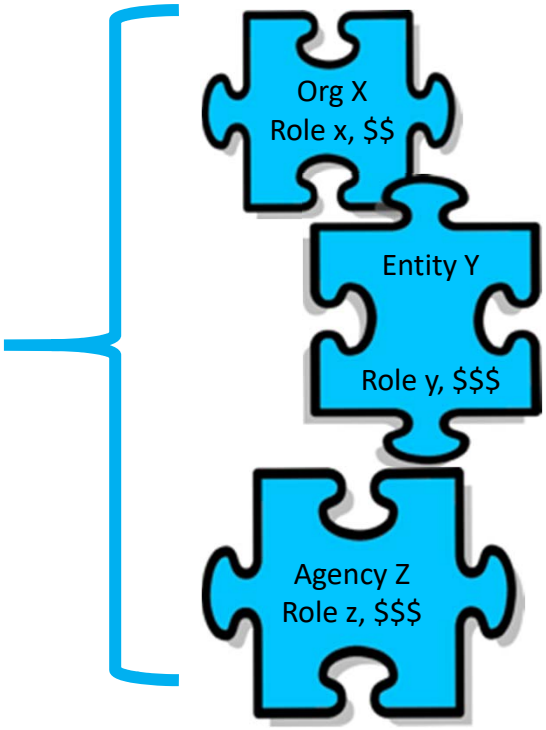
Why do our grand visions – that are **bigger than any one of our orgs/agencies** can address - have trouble reaching the goal?

Goal

Build the best possible
Earth System
Prediction Capability

How to Optimally Assemble & Organize
Function/Role
Constrain Cost
Deliver On Time
Reduce Risk
Etc

Admittedly a hard and complex problem to design and implement a solution



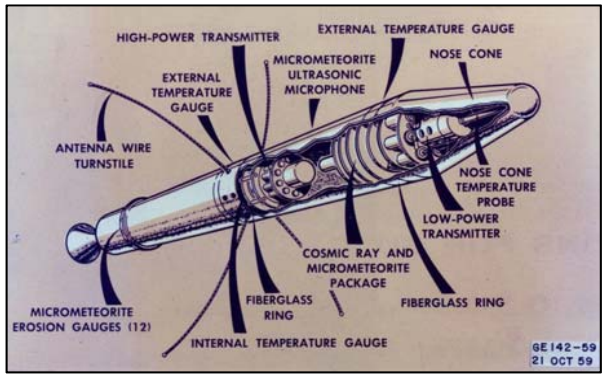
System Engineering

A branch of engineering which concentrates on understanding, designing and managing complex systems, namely systems of interworking components that synergistically work together to perform a useful function (e.g. spacecraft, robotics, software, manufacturing processes, communication systems, healthcare, defense, etc).

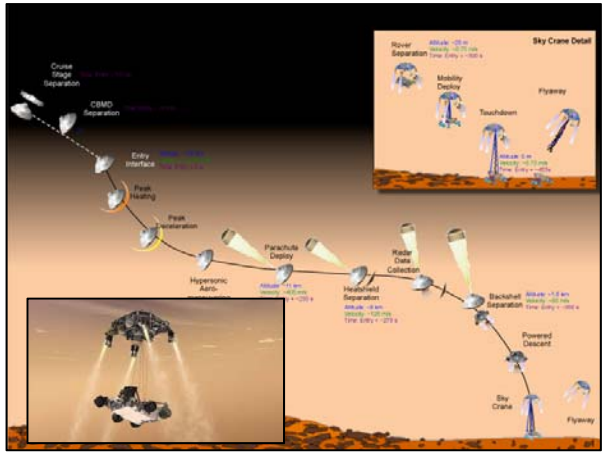
It deals with requirements development, logistics, team coordination, testing and evaluation, costs, reliability, work processes, optimization, risk management, and often the overlaps between technical and human systems.

Relatively New Field
Origins ~ 1940s
First Professional Society ~1990

Explorer I - 1958



Curiosity - 2012



Flight Projects – SE Depth and Breadth

In early days, a System Engineer would mostly need to account for the various hardware subsystems within a flight project.

Today, the **complexity** of the mission and its life cycle require vastly **greater demands on the system engineering** component of the mission – **involving significantly more than hardware**:

- Formulation and Design
- System and subsystem reliability
- Technical, cost and schedule fidelity and risks
- International and Commercial-Gov't Partnerships
- Science requirements and return
- Science/Applications vs Technical trades and descope options
- Verification, Validation and Uncertainty Quantification
- Etc

System Engineering is intrinsic to keeping eyes on the prize and reaching the goal

Types of System of Systems (SoS)

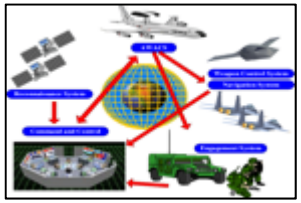
Type	Definition
Virtual	Virtual SoS lack a central management authority and a centrally agreed-on purpose for the system of systems. Large-scale behavior emerges—and may be desirable—but this type of SoS must rely on relatively invisible mechanisms to maintain it.
Collaborative	In collaborative SoS, the component systems interact more or less voluntarily to fulfill agreed-on central purposes. The Internet is a collaborative system. The Internet Engineering Task Force works out standards but has no power to enforce them. The central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards.
Acknowledged	Acknowledged SoS have recognized objectives, a designated manager, and resources. However, the constituent systems retain their independent ownership, objectives, funding, development, and sustainment approaches. Changes in the systems are based on collaboration between the SoS and the system.
Directed	Directed SoS are those in which the integrated system of systems is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might want to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose.

MITRE Guide to SE, 2014

Formalism and Maturity for Systems of Systems

- The formal practice and maturity of Systems Engineering (SE) has yielded classifications of SoS relevant to the scope of our ESP enterprise.
- Within this system, our ESP enterprise would probably be classified as Collaborative.
- Thus, while we may see the ESP enterprise as an ecosystem that is challenging to corral and advance, to the SE community of practice, ESP represents one example in their subject of study and practice.

Applications of Systems (of Systems) Engineering



Defense Systems

DoD, 2008: Systems Engineering Guide for Systems of Systems

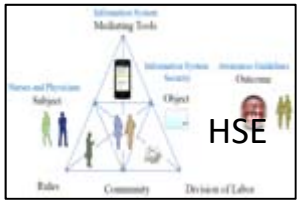
In other sectors, where lives, property, and our prosperity matter, top-down systems engineering and SoS thinking are formally being embraced.

Global Communications Systems

Bhasin, Kul & Hayden, Jeffrey. (2008). Architecting communication network of networks for Space System of Systems. 1 - 7. 10.1109/SYSOSE.2008.4724153.

Homeland Security

Ingber, G. L, W. E. Bunting, D. M. Laredo, M.K. Tun, 2017: Guide for Creating Useful Architectures, Homeland Security Systems Engineering and Development Institute, Version 1.1, Case Number 17-4589 / DHS reference number 16-J-00097-02. (see mitre.org).

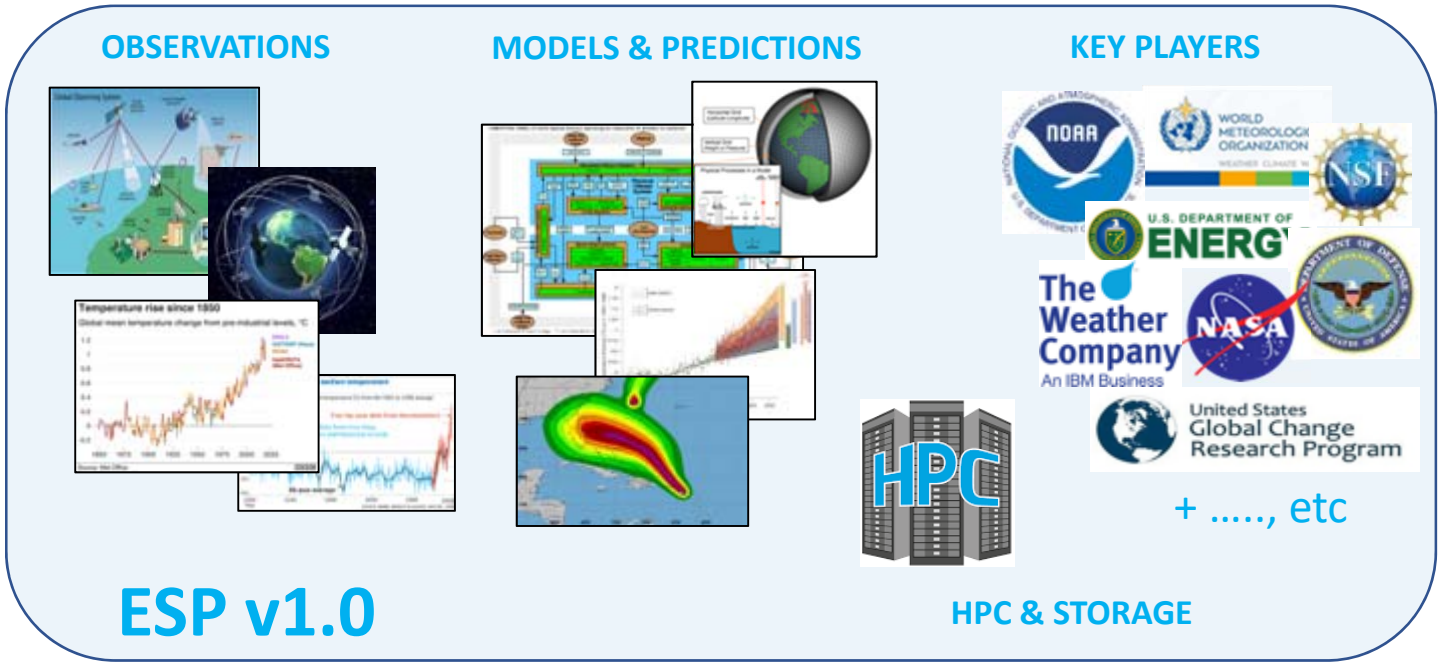


Healthcare Systems

NAE-NIM, 2005: Building a Better Delivery System, A New Engineering/Health Care Partnership, National Academy of Engineering (US) and Institute of Medicine (US) Committee on Engineering and the Health Care System; Editors: P Reid, W Compton, H Grossman, and Fanjiang. Washington (DC): National Academies Press (US); 2005. ISBN-10: 0-309-09643-X

Earth System Prediction – v1.0

At present, we have a "collaborative" system of systems (SoS), developed over the last 50+ years in a somewhat ad hoc and opportunistic manner, that represents our **present-day Earth System Prediction capability.**



- Does the importance of this system warrant a SoS analysis and assessment?
- Would such an analysis and assessment, using practiced expertise, help to objectively identify barriers and pathways for getting to the improvements we seek?

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MITRE Guide to SE, 2014

By acknowledging the systems and systems landscape of our ESP enterprise, are there means to better optimize how we assemble the puzzle pieces for our problem?

- Would there be value in doing a systems of systems analysis on the our current ESP enterprise?
- Would there be value in architecting a top down approach for a (hypothetical?) ESP ?
- Could the differences between what we have and this architecture help define a roadmap and/or prioritize advances?
- Would there be value in helping move our current ESP enterprise from a Collaborative to an Acknowledged SoS?

Not a panacea – but maybe an aid in taking our next big steps

A Systems of Systems (SoS) Perspective For Addressing Earth System Prediction

Quantity of Interest

Planetary and local environmental conditions @ time = 0 and ΔT

Break down the complexity using a systems of systems (SoS) / engineering perspective

Judiciously integrate and evolve the underlying components to maximize value and impacts

Science Complexity
Earth System Science

- Carbon
- Water
- Energy
  - Radiation
  - Latent
  - Sensible
  - Kinetic
  - ....
- ...

Technology & Tool Complexity
Observations, Models & Computation

- Satellites
  - Geostationary Imagers
  - Nadir and Limb Sounders
  - Surface Radars
  - Gravity Measurements
  - Hyperspectral Imagers
  - GNSS-RO
  - ....
  - Satellite Bus
  - Avionics
  - Power
  - Instrument
  - Computation
  - ...
- In-situ network
- ...
- Earth System Models
- Process Models
- Regional Downscaling Models
- ...
- HPC systems
- Cloud Storage
- ...

Programmatic & Enterprise Complexity
Civil, Commercial and Social

- *UN*
- *WMO*
- ...
- *NOAA*
- *NASA*
- *DOE*
- ...
- *SpaceX*
- *Planet*
- *Google, AWS*
- ...
- *State Agencies*
- ...

Suggest that this portion of the solution space may warrant approaching more holistically and formally as a system of systems to aid in advancing ESP

Summary messages and recommendation

Along with the many good RFI/Roundtable/Workshop ideas put forth for advancing our science knowledge and technological capabilities relevant to Earth System Predictability, and the associated/anticipated calls for increases in funding to implement those ideas, **is a (humble) suggestion to explore a more formal application of systems engineering to our Earth system prediction (ESP) enterprise**.

This recommendation stems from **the need to account for the complexities associated with the relevant and rapidly evolving science, tools and technology, and inter-agency and enterprise landscapes**, when making judicious choices about how to advance ESP, and the **significant societal benefits** associated with it.

In addition to having great ideas, a captivating vision, and the associated plans (which an SoS perspective might aid), is the need to have **an ability to execute the overall vision and plans**. Is there an need for a **coordinating office or body** that could better foster / direct effort and resources, one that takes into account the strengths and complementary elements of the various agencies and commercial enterprises that have a role and stake in contributing to this critical national capability?

Recommendation – Assemble a Tiger Team with SoS expertise to report on the value of more formally engaging a SoS perspective in an ongoing basis to help guide our road mapping and prioritizations to advance ESP.